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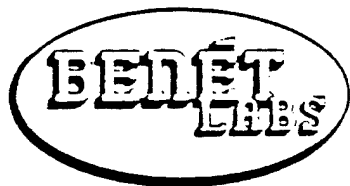
# BENÉT INTERNAL TECHNICAL REPORT

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## UTILIZATION OF ION CHROMATOGRAPHY AND STATISTICS TO DETERMINE IMPORTANT ACIDS IN CHROMIUM PLATING AND ELECTROPOLISHING SOLUTIONS

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# **Utilization of Ion Chromatography and Statistics to Determine Important Acids in Chromium Plating and Electropolishing Solutions**

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## **Abstract**

Inadequate monitoring of sulfuric and chromic acids in chromium plating solutions and phosphoric and sulfuric acids in electropolishing solutions can cause serious problems for the chromium plating industry, such as poor quality products, wasted human resources, and wasted electrical energy. Current instrumental analysis methods, both offline and online, for these acids either do not result in acceptable precisions or are time consuming. Two similar methods, which are improvements on existing ion chromatographical methods, are presented here that provides acceptable analysis and monitoring of these acids in this chromium plating process.

## **Keywords**

instrumental analysis, offline monitoring, online monitoring, sulfuric acid, chromic acid, phosphoric acid, chromium plating solutions, electropolishing solutions, ion chromatography, statistics

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## Introduction

Inadequate monitoring of sulfuric and chromic acids in chromium plating solutions and phosphoric and sulfuric acids in electropolishing solutions can cause serious problems for the chromium plating industry, such as poor quality products, wasted human resources, and wasted electrical energy. Current instrumental analysis methods, both offline and online, for these acids either do not result in acceptable precisions or are time consuming (ref 1-5). Two similar methods, which are improvements on existing ion chromatographical methods, are presented which provide acceptable analysis and monitoring of these acids in this chromium plating process coupled with an extensive statistical evaluation of the experimental data.

## Approach

Strict analytical chemistry methods and procedures are followed throughout this experimental section. An excellent source of reference for these methods and procedures is by Fritz and Schenk (ref 6).

The analytical system used is the Dionex 2020i ion chromatograph (Dionex Corporation, Sunnyvale, CA). Dionex publishes a manual which is an excellent source of reference for operation and maintenance of this chromatographic system (ref 7).

The initial conditions for the autosampler module, analytical pump, conductivity detector, and advanced chromatography modules are given in Tables 1-4, respectively.

Fill the system reservoirs with the appropriate method eluent and regenerate. The analytical pump used for the eluent must be completely purged of air every time the eluent reservoir is filled. Dionex claims that a proper functioning analytical pump is necessary for acceptable precisions.

The conductivity detector should be periodically calibrated to 147  $\mu$ S using 0.00100 M potassium chloride.

The initial programing conditions for the system computer/controller module are the equilibration program (P-1), analysis program (P-2), and the halt program (P-H) given in Tables 5-7, respectively. The initial scheduling conditions for this same module for the equilibration, analysis, and halt programs are given in Table 8.

The initial programing and scheduling conditions for the system computer/integrator are given in Table 9.

### **Determination of chromic or sulfuric acid in chromium plating solutions**

Two analytical reagent grade standard solutions are required. The first is a  $2.95 \pm 0.01$  g/l sulfuric acid solution that meets American Chemical Society (ACS) and American Society For Testing Materials (ASTM) Standards (ref 8-9). The second is a  $250 \pm 1$  g/l chromic acid solution that meets ACS and Federal Standards (ref 10-11). E. M. Science reagent grade chromium trioxide is the only material found in our experience that meets ACS standards allowing a maximum of 0.005% sulfate. Two other reagent grade solutions are also required: a  $0.38 \pm 0.02$  g/l sodium carbonate eluent solution and a  $1.38 \pm 0.04$  g/l sulfuric acid regenerate solution.

Preparation of a chromium plating solution standard for ion chromatographic analysis requires that one milliliter of each of the analytical reagent grade standard solutions (sulfuric and chromic acids) prepared above are diluted to the mark with deionized water in a 250 ml volumetric flask. Only two chromium plating solution samples (X & Y) can be run at a time since each of these two sample solutions are split for a total of four solutions (X-1, X-2, Y-1, and Y-2).

Preparation of a chromium plating solution sample for ion chromatographic analysis requires that one milliliter of each split solution is diluted to the mark with deionized water in a 250 ml volumetric flask.

The chromium plating solution standard (S) and samples (2-1, 2-2, 8-1, and 8-2) for ion chromatographic analysis are placed in the autosampler cassettes in thirty sealed 5 ml vials according to the order outlined in Table 10. Using the same order, these cassettes are placed in the autosampler module.

A chromatograph is produced for each chromium plating solution standard (S) and samples (2-1, 2-2, 8-1, and 8-2) placed in the autosampler for analysis according to the order outlined in Table 10. For these standard and sample solutions, peak heights are given for the acid and since standard solution concentrations are known, sample solution concentrations can be calculated. Then precisions are calculated using an extensive statistical method for reliability determinations.

### **Determination of sulfuric or phosphoric acid in electropolishing solutions**

One analytical reagent grade standard solution is required. It contains  $685 \pm 1$  g/l phosphoric acid and  $845 \pm 1$  g/l sulfuric acid. This standard solution is prepared and standardized using a previous method by this author (ref 12). Two other reagent grade solutions are required: a  $0.100 \pm 0.005$  g/l sodium carbonate eluent solution and a  $1.38 \pm 0.04$  g/l sulfuric acid regenerate solution.



Preparation of a electropolishing solution standard for ion chromatographic analysis requires that 0.400 ml of the analytical reagent grade standard solution (phosphoric and sulfuric acid mixture) prepared above is diluted to the mark with deionized water in a 2000 ml volumetric flask. Up to two electropolishing solution samples (X & Y) can be run at a time since each of these two sample solutions are split for a total of four solutions (X-1, X-2, Y-1, and Y-2). Only one sample solution is run (8P) here which is split into solutions 8P-1, and 8P-2.

Preparation of a electropolishing solution sample for ion chromatographic analysis requires that 0.400 ml of the split solution is diluted to the mark with deionized water in a 2000 ml volumetric flask.

The electropolishing solution standard (S) and samples (8P-1 and 8P-2) for ion chromatographic analysis are placed in the autosampler cassettes in 18 sealed 5 ml vials according to the order outlined in Table 11. Using the same order, these cassettes are placed in the autosampler module.

A chromatograph is produced for each electropolishing solution standard (S) and samples (8P-1 and 8P-2) placed in the autosampler for analysis according to the order outlined in Table 11. For these standard and sample solutions, peak heights are given for the acid and since standard solution concentrations are known, sample solution concentrations can be calculated. Then precisions are calculated using an extensive statistical method for reliability determinations.

## Results and Discussion

A statistical analysis is necessary to determine the reliability of the experimental ion chromatographic sample data in order to adequately monitor a given acid in the chromium plating process. The statistical evaluation has two parts.

In the first part of the statistical evaluation, samples are split and each split solution is analyzed in triplicate. Tables 12 and 13 give the experimental peak height data for the acid standard and split sample solutions.. The mean  $\bar{X}(\text{avg})$  and sample standard deviation  $S(n-1)$  are calculated for each of these samples and its associated standard. The pooled sample standard deviation  $S_p$  is calculated from the standard deviation of each sample and its associated standard as follows:

$$S_p = \left[ \frac{(S1^{**2} + S2^{**2})}{2} \right]^{**0.5} \quad (1)$$

In addition, the ninety-five percent confidence level  $C(95\%)$  is calculated from the above quantities for each sample and its associated standard:

$$C(95\%) = (2.266)(S_p) \frac{\text{acid std. conc}}{\text{std. } X(\text{avg})} \quad (2)$$

The concentration data are given for the experimental peak height data in Tables 14 and 15. Again, the mean  $X(\text{avg})$  and sample standard deviation  $S(n-1)$  are calculated for each of these samples.

The concentration data of the split sample solutions are given in Table 16 and 17. As above, the mean, sample standard deviation, and pooled sample standard deviation are calculated. In addition, another quantity is calculated called the T-test value (T) for each sample solution from the following:

$$T = (1.225) \frac{X_1(\text{avg}) - X_2(\text{avg})}{S_p} \quad (3)$$

The experimental data of the split solutions of a sample solution are compared to a 2.776 value using the T-test to see if they are statistically from the same original sample solution to a 95% confidence level. A sample solution passes this T-test if its resultant absolute value is less than the 2.776 value. This T-test addresses the reliability dilemma mentioned above since it either accepts or rejects a sample solution analysis; samples solutions that fail the T-test are statistically dissimilar and are re-sampled and re-analyzed.

In the second part of the statistical evaluation, the mean  $X(\text{avg})$  and normal population standard deviation ( $S_n$ ) are calculated for the six respective replicates of the sample solutions that have passed the T-test. Since this was the case, the concentration data for the solutions are given in Table 18 and 19.

It is useful to evaluate the variations in precision for the materials and methods used. Tables 20-23 present the data for the one milliliter micropipet, the 250 ml class A volumetric flasks, the 250 g/l chromic acid standard solution and the 2.95 g/l sulfuric acid standard solution, respectively. Variations in precision are also evaluated for the ion chromatographic system. Table 24 and 25 present the data for 24 consecutive replicates of the 2.95 g/l sulfuric acid and 2.50 g/l chromic acid standard solutions which are equivalent to the same number of runs as analyzing the split solutions of sample solutions 2 and 8. Tables 26-29 present the data for the 0.400 ml micropipet, the 2000 ml class A volumetric flask, the 685 g/l phosphoric acid standard solution and the 845 g/l sulfuric acid standard solution, respectively. Variations in precision are also evaluated for the ion chromatographic system. Table 30 and 31 presents the data for 6 consecutive replicates of the 685 g/l phosphoric acid and 845 g/l sulfuric acid

standard solutions. It is clear that the ion chromatographic system contributes the greatest amount of variation in precision compared to all other sources given for both of the above methods.

The data shows that these improved methods are sufficient to monitor these acids in the chromium plating process. The optimum operating range of sulfuric acid in chromium plating solutions is 2.50 - 3.00 g/l and the resulting precisions are in the range of 0.03 - 0.20 g/l. The optimum operating range of chromic acid in chromium plating solutions is 240 - 260 g/l and the resulting precisions are in the range of 1 - 9 g/l. The optimum operating range of phosphoric in electropolishing solutions is 640 - 730 g/l and the resulting precisions are in the range of 2 - 7 g/l. The optimum operating range of sulfuric acid in electropolishing solutions is 795 - 895 g/l and the resulting precisions are in the range of 2 - 8 g/l. These precisions provide adequate monitoring of these chromium plating process acids and are supported by eight years of testing.

**Table 1. Initial Conditions for the Autosampler Module**

|                      |               |
|----------------------|---------------|
| <b>Local/Remote:</b> | Local         |
| <b>Run/Hold:</b>     | Hold Then Run |
| <b>Status:</b>       | Search        |
| <b>Size:</b>         | 5 ml          |
| <b>Type:</b>         | Sample        |
| <b>Inj:</b>          | 1             |
| <b>Tray:</b>         | In/Empty      |
| <b>Type:</b>         | Loop          |
| <b>Mode:</b>         | Prop          |
| <b>Bleed:</b>        | On            |
| <b>Inj/Vial:</b>     | 1             |

**Table 2. Initial Conditions for the Analytical Pump Module**

|                                                |        |
|------------------------------------------------|--------|
| <b>Local/Remote:</b>                           | Remote |
| <b>Start/Stop:</b>                             | Stop   |
| <b>Flow (ml/min):</b>                          | 2.3    |
| <b>Pressure Limit Select Low Alarm (psi):</b>  | 100    |
| <b>Pressure Limit Select High Alarm (psi):</b> | 1000   |
| <b>Valve Pressure (psi Argon):</b>             | 100    |

**Table 3. Initial Conditions for the Conductivity Detector Module**

|                           |        |
|---------------------------|--------|
| <b>Local/Remote:</b>      | Remote |
| <b>Cell:</b>              | On     |
| <b>Auto Offset:</b>       | Off    |
| <b>Temp. Comp.:</b>       | 0      |
| <b>Output Range (μS):</b> | 30     |

**Table 4. Initial Conditions for the Advanced Chromatography Module**

|                                         |                      |
|-----------------------------------------|----------------------|
| <b>Load/Inject:</b>                     | Inject               |
| <b>Valve A:</b>                         | Off                  |
| <b>Valve B:</b>                         | Off                  |
| <b>Local/Remote:</b>                    | Remote               |
| <b>Separator Column:</b>                | HPIC-AG4<br>(Dionex) |
| <b>Suppressor Column:</b>               | AMMS<br>(Dionex)     |
| <b>Valve Pressure (psi Argon):</b>      | 100                  |
| <b>Regenerate Flow:</b>                 | 5ml/min              |
| <b>Regenerate Pressure (psi Argon):</b> | 6                    |

**Table 5. Computer/Controller Equilibration Program One\***

| Time (min) | Load/Inject | Valve B | Offset | Auto-Relays | End Run |
|------------|-------------|---------|--------|-------------|---------|
| 0.0        | Inject      | On      | Off    | Off         | Off     |
| 5.0        | Inject      | On      | Off    | Off         | Off     |
| 30.0       | Inject      | On      | Off    | Off         | On      |

**Table 6. Computer/Controller Analysis Program Two\***

| Time (min) | Load/Inject | Valve B | Offset | Auto-Relays | End Run |
|------------|-------------|---------|--------|-------------|---------|
| 0.0        | Load        | On      | Off    | Off         | Off     |
| 0.1        | Load        | On      | Off    | #2          | Off     |
| 0.2        | Load        | On      | Off    | Off         | Off     |
| 2.2        | Load        | On      | On     | Off         | Off     |
| 2.3        | Inject      | On      | On     | #1          | Off     |
| 10.0       | Inject      | On      | On     | Off         | On      |

\* Eluent flow rate is 2.3 ml/min., eluent port #3 is used, temp. select is zero, valve A is continually off, temp. comp. is 1.7, cond. setting full scale is 30  $\mu$ S, AC outlets are all continually off.

**Table 7. Computer/Controller Halt Program Halt**

| Time (min) | Load/Inject | Valve B | Offset | Auto-Relays | End Run |
|------------|-------------|---------|--------|-------------|---------|
| 0.0        | Inject      | Off     | Off    | Off         | On      |

Eluent flow rate is 0.0 ml/min., no eluent port is selected, temp. select is zero, valve A is continually off, temp. comp. is zero, cond. setting full scale is 30  $\mu$ S, AC outlets are all off.

**Table 8. Computer/Controller Analysis Schedule**

| Step | Program | Iterations |
|------|---------|------------|
| 1    | 1       | 1          |
| 2    | 2       | 30         |
| 3    | Halt    | 1          |
| 4-9  | Halt    | 0          |

**Table 9. Computer/Integrator Analysis Program**

Ready  
Date"  
Time"  
AT=1024  
PH=1  
PT=5000  
FI=1. FE=1. MN=0.  
Press 'Enter' To Skip Entry  
File Name="  
Time Function Value  
TT=  
Method Number: MN=0  
End of Dialog

**Table 10. Order of Sample Vials in the Autosampler Cassettes for Sulfuric and Chromic Acid in Chromium Plating Solution**

| Sample Vial # | Standard/Sample # |
|---------------|-------------------|
| 1             | S                 |
| 2             | S                 |
| 3             | S                 |
| 4             | S                 |
| 5             | S                 |
| 6             | 2-1               |
| 7             | S                 |
| 8             | 2-1               |
| 9             | S                 |
| 10            | 2-1               |
| 11            | S                 |
| 12            | 2-2               |
| 13            | S                 |
| 14            | 2-2               |
| 15            | S                 |
| 16            | 2-2               |
| 17            | S                 |
| 18            | 8-1               |
| 19            | S                 |
| 20            | 8-1               |
| 21            | S                 |
| 22            | 8-1               |
| 23            | S                 |
| 24            | 8-2               |
| 25            | S                 |
| 26            | 8-2               |
| 27            | S                 |
| 28            | 8-2               |
| 29            | S                 |
| 30            | Deionized Water   |

**Table 11. Order of Sample Vials in the Autosampler Cassettes for Phosphoric and Sulfuric Acid in Electropolishing Solution**

| Sample Vial # | Standard/Sample # |
|---------------|-------------------|
| 1             | S                 |
| 2             | S                 |
| 3             | S                 |
| 4             | S                 |
| 5             | S                 |
| 6             | 8P-1              |
| 7             | S                 |
| 8             | 8P-1              |
| 9             | S                 |
| 10            | 8P-1              |
| 11            | S                 |
| 12            | 8P-2              |
| 13            | S                 |
| 14            | 8P-2              |
| 15            | S                 |
| 16            | 8P-2              |
| 17            | S                 |
| 18            | Deionized Water   |

**Table 12. Experimental Ion Chromatograph Peak Height Data for Sulfuric and Chromic Acid in Chromium Plating Sample Solutions**

| Replicate | Sulfuric Acid |            |            | Chromic Acid |            |            |
|-----------|---------------|------------|------------|--------------|------------|------------|
|           | Standard S    | Sample 2-1 | Standard S | Sample 2-2   | Standard S | Sample 2-2 |
| 1         | 185033        | 165973     | 180188     | 168167       | 638810     | 666837     |
| 2         | 168196        | 159359     | 171808     | 162845       | 680478     | 663962     |
| 3         | 170185        | 169031     | 168119     | 165749       | 685812     | 689280     |
| X(avg)    | 174471        | 164788     | 173372     | 165587       | 668366     | 673359     |
| S(n-1)    | 9200          | 4944       | 6184       | 2645         | 25739      | 13862      |
| Sp        | 8171          |            | 4756       |              | 20671      |            |
| C(95%)    | 0.312         |            | 0.182      |              | 17.5       | 14.8       |

| Replicate | Sulfuric Acid |            |            | Chromic Acid |            |            |
|-----------|---------------|------------|------------|--------------|------------|------------|
|           | Standard S    | Sample 8-1 | Standard S | Sample 8-2   | Standard S | Sample 8-2 |
| 1         | 170185        | 163899     | 173776     | 163668       | 667793     | 678899     |
| 2         | 176065        | 165987     | 169989     | 163303       | 671066     | 682189     |
| 3         | 173267        | 159973     | 170932     | 161416       | 672645     | 687026     |
| X(avg)    | 173172        | 163286     | 171566     | 162796       | 670501     | 682704     |
| S(n-1)    | 2941          | 3053       | 1971       | 1209         | 2474       | 4087       |
| Sp        | 2998          |            | 1635       |              | 3378       |            |
| C(95%)    | 0.115         |            | 0.063      |              | 2.9        | 12.4       |

Raw peak height data is in integrator units (IC). Initially four equilibration standards are run before standard one. These are standard solutions (S) and split sample solutions (2-1, 2-2, 8-1 and 8-2) after a 1:250 dilution.



**Table 13. Experimental Ion Chromatograph Peak Height Data for Phosphoric and Sulfuric Acid in Electropolishing Sample Solutions**

| Replicate | Phosphoric Acid |             |            |             | Sulfuric Acid |             |            |             |
|-----------|-----------------|-------------|------------|-------------|---------------|-------------|------------|-------------|
|           | Standard S      | Sample 8P-1 | Standard S | Sample 8P-2 | Standard S    | Sample 8P-1 | Standard S | Sample 8P-2 |
| 1         | 562500          | 509200      | 573900     | 512700      | 813800        | 770200      | 815700     | 762300      |
| 2         | 572000          | 507700      | 575800     | 516100      | 821400        | 764600      | 813600     | 763200      |
| 3         | 573300          | 509100      | 578700     | 517100      | 819500        | 763000      | 810400     | 760500      |
| X(avg)    | 569267          | 508667      | 576133     | 515300      | 818233        | 765933      | 813233     | 762000      |
| S(n-1)    | 5896            | 839         | 2417       | 2307        | 3955          | 3781        | 2669       | 1375        |
| Sp        | 4211            |             | 2363       |             | 3869          |             | 2123       |             |
| C(95%)    | 11.5            |             | 6.4        |             | 9.1           |             | 5.0        |             |

Raw peak height data is in integrator units (IU). Initially four equilibration standards are run before standard one. These are standard solutions (S) and split sample solutions (8P-1 and 8P-2) after a 1:5000 dilution.

**Table 14. Concentration Data for Sulfuric and Chromic Acid in Chromium Plating Sample Solutions**

| Replicate | Sulfuric Acid |            |            |            | Chromic Acid |            |            |            |
|-----------|---------------|------------|------------|------------|--------------|------------|------------|------------|
|           | Sample 2-1    | Sample 2-2 | Sample 8-1 | Sample 8-2 | Sample 2-1   | Sample 2-2 | Sample 8-1 | Sample 8-2 |
| 1         | 2.63          | 2.74       | 2.83       | 2.76       | 261          | 260        | 254        | 249        |
| 2         | 2.78          | 2.78       | 2.77       | 2.82       | 244          | 247        | 254        | 252        |
| 3         | 2.92          | 2.89       | 2.71       | 2.77       | 251          | 241        | 255        | 263        |
| X(avg)    | 2.77          | 2.80       | 2.77       | 2.78       | 252          | 249        | 254        | 255        |
| S(n-1)    | 0.145         | 0.078      | 0.060      | 0.032      | 8.54         | 9.71       | 0.577      | 7.37       |

Concentration data is in g/l.

**Table 15. Concentration Data for Phosphoric and Sulfuric Acid in Electropolishing Sample Solutions**

| Replicate | Phosphoric Acid |             | Sulfuric Acid |             |
|-----------|-----------------|-------------|---------------|-------------|
|           | Sample 8P-1     | Sample 8P-2 | Sample 8P-1   | Sample 8P-2 |
| 1         | 620             | 612         | 800           | 790         |
| 2         | 608             | 614         | 787           | 793         |
| 3         | 608             | 612         | 787           | 793         |
|           |                 |             |               |             |
| X(avg)    | 612             | 613         | 791           | 792         |
| S(n-1)    | 6.9             | 1.1         | 7.5           | 1.8         |

Concentration data is in g/l.

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**Table 16. Concentration Data for Sulfuric and Chromic Acid in Chromium Plating Sample Solutions**

| Split Solutions  | Sulfuric Acid     |       |                   |       | Chromic Acid      |      |                   |      |
|------------------|-------------------|-------|-------------------|-------|-------------------|------|-------------------|------|
|                  | Sample Solution 2 |       | Sample Solution 8 |       | Sample Solution 2 |      | Sample Solution 8 |      |
|                  | 2-1               | 2-2   | 8-1               | 8-2   | 2-1               | 2-2  | 8-1               | 8-2  |
| X(avg)           | 2.77              | 2.80  | 2.77              | 2.78  | 252               | 249  | 254               | 255  |
| S(n-1)           | 0.145             | 0.078 | 0.060             | 0.032 | 8.54              | 9.71 | 0.577             | 7.37 |
| Sp               | 0.116             |       | 0.048             |       | 9.14              |      | 5.22              |      |
| T-test value (T) | 0.316             |       | 0.254             |       | 0.402             |      | 0.234             |      |

Concentration data is in g/l. These are the split sample solutions (2-1, 2-2, 8-1 and 8-2) from original sample solutions 2 and 8.

**Table 17. Concentration Data for Phosphoric and Sulfuric Acid in Electropolishing Sample Solutions**

| Sample Solution 8P |      |      |               |      |
|--------------------|------|------|---------------|------|
| Phosphoric Acid    |      |      | Sulfuric Acid |      |
| Split Solutions    | 8P-1 | 8P-2 | 8P-1          | 8P-2 |
| X(avg)             | 612  | 613  | 791           | 792  |
| S(n-1)             | 6.9  | 1.1  | 7.5           | 1.8  |
| T-test value (T)   | 0.13 |      | 0.17          |      |

Concentration data is in g/l.

**Table 18. Reported Concentration Data for Sulfuric and Chromic Acid in Chromium Plating Sample Solutions**

| Replicate | Sulfuric Acid     |                   | Chromic Acid      |                   |
|-----------|-------------------|-------------------|-------------------|-------------------|
|           | Sample Solution 2 | Sample Solution 8 | Sample Solution 2 | Sample Solution 8 |
| 1         | 2.63              | 2.83              | 261               | 254               |
| 2         | 2.78              | 2.77              | 244               | 254               |
| 3         | 2.92              | 2.71              | 251               | 255               |
| 4         | 2.74              | 2.76              | 260               | 249               |
| 5         | 2.78              | 2.82              | 247               | 252               |
| 6         | 2.89              | 2.77              | 241               | 263               |
| X(avg)    | 2.79              | 2.77              | 251               | 254               |
| Sn        | 0.10              | 0.04              | 8                 | 4                 |

Concentration data is in g/l. Sample solutions 2 and 8 are the unsplit and original sample solutions.

**Table 19. Reported Concentration Data for Phosphoric and Sulfuric Acid in Electropolishing Sample Solutions**

|                  | <b>Phosphoric Acid</b> | <b>Sulfuric Acid</b> |
|------------------|------------------------|----------------------|
| <b>Replicate</b> | <b>Solution 8P</b>     | <b>Solution 8P</b>   |
| 1                | 620                    | 800                  |
| 2                | 608                    | 787                  |
| 3                | 608                    | 787                  |
| 4                | 612                    | 790                  |
| 5                | 614                    | 793                  |
| 6                | 612                    | 793                  |
|                  |                        |                      |
| X(avg)           | 612                    | 792                  |
| Sn               | 4.0                    | 4.5                  |

Concentration data is in g/l. Sample solution 8P is the unsplit and original sample solution.

**Table 20. Precision of Micropipeting One Milliliter**

| <b>Replicate</b> | <b>Volume (ml)</b> |
|------------------|--------------------|
| 1                | 1.0133             |
| 2                | 1.0105             |
| 3                | 1.0140             |
| 4                | 1.0066             |
| 5                | 1.0106             |
| 6                | 1.0065             |
|                  |                    |
| X(avg)           | 1.0102             |
| Sn               | 0.0029             |

**Table 21. Precision of 250 ml Class-A Volumetric Flask**

| <b>Replicate</b> | <b>Volume (ml)</b> |
|------------------|--------------------|
| 1                | 249.54             |
| 2                | 249.47             |
| 3                | 249.47             |
| 4                | 249.45             |
| 5                | 249.50             |
| 6                | 249.51             |
|                  |                    |
| X(avg)           | 249.49             |
| Sn               | 0.03               |

Volumes are calculated from the weight-volume relationship of the contained deionized water solution corrected for temperature.

**Table 22. Precision of 250 g/l Chromic Acid Standard Solution**

| <b>Replicate</b> | <b>CRO<sub>3</sub><br/>Conc. (g/l)</b> |
|------------------|----------------------------------------|
| 1                | 250.5                                  |
| 2                | 250.2                                  |
| 3                | 250.2                                  |
| 4                | 249.8                                  |
| 5                | 250.5                                  |
| 6                | 250.2                                  |
|                  |                                        |
| X(avg)           | 250.2                                  |
| Sn               | 0.2                                    |

Chromic acid concentrations are calculated using Federal Specification O-C-303D.

**Table 23. Precision of 2.95 g/l Sulfuric Acid Standard Solution by Titration**

| <b>Replicate</b> | <b>H<sub>2</sub>SO<sub>4</sub><br/>Conc. (g/l)</b> |
|------------------|----------------------------------------------------|
| 1                | 2.940                                              |
| 2                | 2.945                                              |
| 3                | 2.940                                              |
| 4                | 2.945                                              |
| 5                | 2.935                                              |
| 6                | 2.945                                              |
|                  |                                                    |
| X(avg)           | 2.942                                              |
| Sn               | 0.004                                              |

Sulfuric acid concentrations are calculated using ASTM Standard E233.

**Table 24. Precision of 2.94 g/l Sulfuric Acid Standard Solution by Ion Chromatography**

| Replicate | H <sub>2</sub> SO <sub>4</sub> Peak Height (IU) |
|-----------|-------------------------------------------------|
| 1         | 190949                                          |
| 2         | 188708                                          |
| 3         | 190668                                          |
| 4         | 190147                                          |
| 5         | 190088                                          |
| 6         | 192674                                          |
| 7         | 188182                                          |
| 8         | 187171                                          |
| 9         | 185994                                          |
| 10        | 185739                                          |
| 11        | 188327                                          |
| 12        | 191380                                          |
| 13        | 190464                                          |
| 14        | 185171                                          |
| 15        | 185513                                          |
| 16        | 184750                                          |
| 17        | 189062                                          |
| 18        | 188087                                          |
| 19        | 189516                                          |
| 20        | 185360                                          |
| 21        | 186953                                          |
| 22        | 182093                                          |
| 23        | 187845                                          |
| 24        | 183962                                          |
|           |                                                 |
| X(avg)    | 187866                                          |
| Sn        | 2650                                            |

**Table 25. Precision of 250 g/l Chromic Acid Standard Solution by Ion Chromatography**

| Replicate | CRO <sub>3</sub> Peak Height (IU) |
|-----------|-----------------------------------|
| 1         | 686587                            |
| 2         | 647711                            |
| 3         | 659666                            |
| 4         | 675259                            |
| 5         | 689793                            |
| 6         | 699663                            |
| 7         | 682745                            |
| 8         | 680179                            |
| 9         | 686991                            |
| 10        | 674796                            |
| 11        | 693042                            |
| 12        | 703530                            |
| 13        | 693399                            |
| 14        | 690266                            |
| 15        | 684613                            |
| 16        | 683087                            |
| 17        | 693316                            |
| 18        | 698195                            |
| 19        | 699618                            |
| 20        | 697099                            |
| 21        | 677752                            |
| 22        | 663899                            |
| 23        | 705008                            |
| 24        | 680866                            |
|           |                                   |
| X(avg)    | 685295                            |
| Sn        | 14035                             |

Peak height is in integrator units (IU). Four equilibration replicates were run before the first replicate in this Table; these twenty-four replicates represent the same number of samples run as when sample solutions 2 and 8 are split and run above.

**Table 26. Precision of Micropipeting 0.400 Milliliters**

| Replicate | Volume (ml) |
|-----------|-------------|
| 1         | 0.401       |
| 2         | 0.398       |
| 3         | 0.399       |
| 4         | 0.400       |
| 5         | 0.400       |
| 6         | 0.403       |
|           |             |
| X(avg)    | 0.400       |
| Sn        | 0.002       |

**Table 27. Precision of 2000 ml Class-A Volumetric Flask**

| Replicate | Volume (ml) |
|-----------|-------------|
| 1         | 2002        |
| 2         | 1997        |
| 3         | 1997        |
| 4         | 2001        |
| 5         | 2003        |
| 6         | 1998        |
|           |             |
| X(avg)    | 2000        |
| Sn        | 2           |

Volumes are calculated from the weight-volume relationship of the contained deionized water solution corrected for temperature.

**Table 28. Precision of 685 g/l Phosphoric Acid Standard Solution**

| Replicate | H <sub>3</sub> PO <sub>4</sub> Conc. (g/l) |
|-----------|--------------------------------------------|
| 1         | 684                                        |
| 2         | 685                                        |
| 3         | 685                                        |
| 4         | 684                                        |
| 5         | 685                                        |
| 6         | 684                                        |
|           |                                            |
| X(avg)    | 685                                        |
| Sn        | 1                                          |

Phosphoric acid concentrations are calculated by a chemical analysis method by this author (12).

**Table 29. Precision of 845 g/l Sulfuric Acid Standard Solution by Titration**

| Replicate | H <sub>2</sub> SO <sub>4</sub> Conc. (g/l) |
|-----------|--------------------------------------------|
| 1         | 845                                        |
| 2         | 845                                        |
| 3         | 846                                        |
| 4         | 845                                        |
| 5         | 844                                        |
| 6         | 845                                        |
|           |                                            |
| X(avg)    | 845                                        |
| Sn        | 1                                          |

Sulfuric acid concentrations are calculated by a chemical analysis method by this author (12).

**Table 30. Precision of 685 g/l  
Phosphoric Acid Standard Solution  
by Ion Chromatography**

| Replicate | H <sub>3</sub> PO <sub>4</sub> Peak<br>Height (IU) |
|-----------|----------------------------------------------------|
| 1         | 562500                                             |
| 2         | 572000                                             |
| 3         | 573300                                             |
| 4         | 573900                                             |
| 5         | 575800                                             |
| 6         | 578700                                             |
|           |                                                    |
| X(avg)    | 572700                                             |
| Sn        | 5032                                               |

**Table 31. Precision of 845 g/l  
Sulfuric Acid Standard Solution by  
Ion Chromatography**

| Replicate | H <sub>2</sub> SO <sub>4</sub> Peak<br>Height (IU) |
|-----------|----------------------------------------------------|
| 1         | 813800                                             |
| 2         | 821400                                             |
| 3         | 819500                                             |
| 4         | 815700                                             |
| 5         | 813600                                             |
| 6         | 810400                                             |
|           |                                                    |
| X(avg)    | 815700                                             |
| Sn        | 3720                                               |

Peak height is in integrator units (IU). Four equilibration replicates were run before the first replicate in this Table.



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